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Power System Mass Analysis for Hydrogen Reduction Oxygen Production on the Lunar Surface

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Power System Mass Analysis for Hydrogen Reduction Oxygen Production on the Lunar Surface

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Abstract

The production of oxygen from the lunar regolith requires both thermal and electrical power in roughly similar proportions. This unique power requirement is unlike most applications on the lunar surface. To efficiently meet these requirements, both solar PV array and solar concentrator systems were evaluated. The mass of various types of photovoltaic and concentrator based systems were calculated to determine the type of power system that provided the highest specific power. These were compared over a range of oxygen production rates. Also a hybrid type power system was also considered. This system utilized a photovoltaic array to produce the electrical power and a concentrator to provide the thermal power. For a single source system the three systems with the highest specific power were a flexible concentrator/Stirling engine system, a rigid concentrator/Stirling engine system and a tracking triple junction solar array system. These systems had specific power values of 43, 34, and 33 W/kg, respectively. The hybrid power system provided much higher specific power values then the single source systems. The best hybrid combinations were the triple junction solar array with the flexible concentrator and the rigid concentrator. These systems had a specific power of 81 and 68 W/kg, respectively.

Introduction

Producing oxygen from lunar surface material is a very power intensive process. The power system must be capable of providing electrical and thermal power for the oxygen production process. The comparison between the amount of thermal and electrical power required for the oxygen production process are similar. The analysis described in Reference 1 has shown that the electrical and thermal power requirements are similar in magnitude. The required thermal and electrical power, from this previous analysis, is shown in Figure 1 for a range of oxygen production rates.

This combination of electrical and thermal power requirements is unlike most other types of power consuming applications identified for the lunar surface. Most other applications usually require a majority of electrical power with a small fraction needed as thermal power. The need for similar levels of electrical and thermal power, for the oxygen production application, will influence the selection of the type of power system. To provide for these power requirements and minimize the mass and size of the power system will require a different approach then that used for other lunar power applications.

To provide both electrical and thermal power, either solar photovoltaic arrays or a solar concentrator can be utilized. Also a combination of both of these types of power production systems can be utilized. Each of these solar energy conversion systems have advantages and disadvantages depending on the application and each of these systems will scale differently to the total power level required. One means of evaluating which type of system or combination of systems is preferable is to use the total power production system mass as a means of comparison. To achieve this each system will need to be broken down into their main components and the mass of each component scaled based on the power level required.

Photovoltaic Array System

A common type of power system usually proposed for lunar daytime operations is a photovoltaic array based system as shown in Figure 2. This type of system can meet most electrical power requirements, is easily stowed for launch and easily deployed once on the surface. Also the technology for

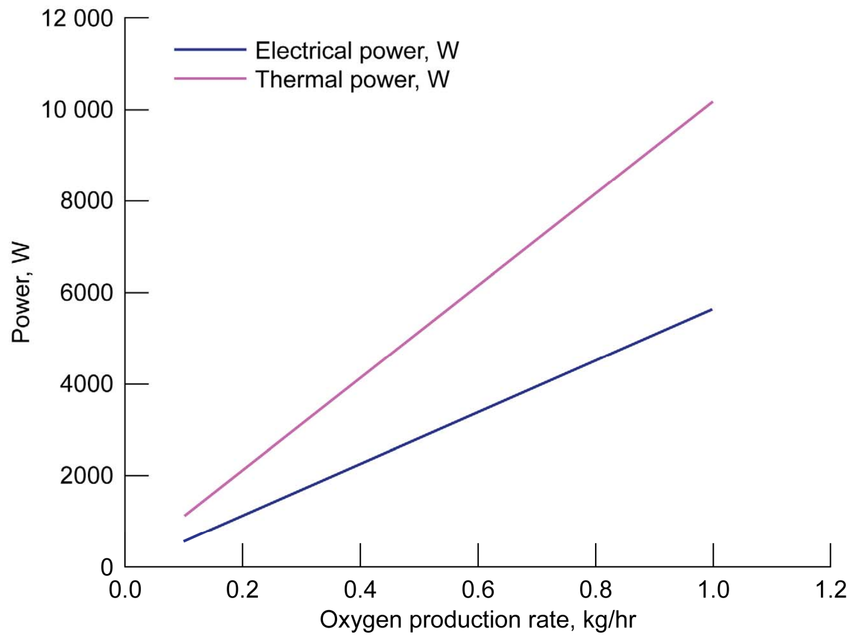

Figure 1.—Thermal and electrical power requirements for a range of oxygen production rates (Ref. 1).

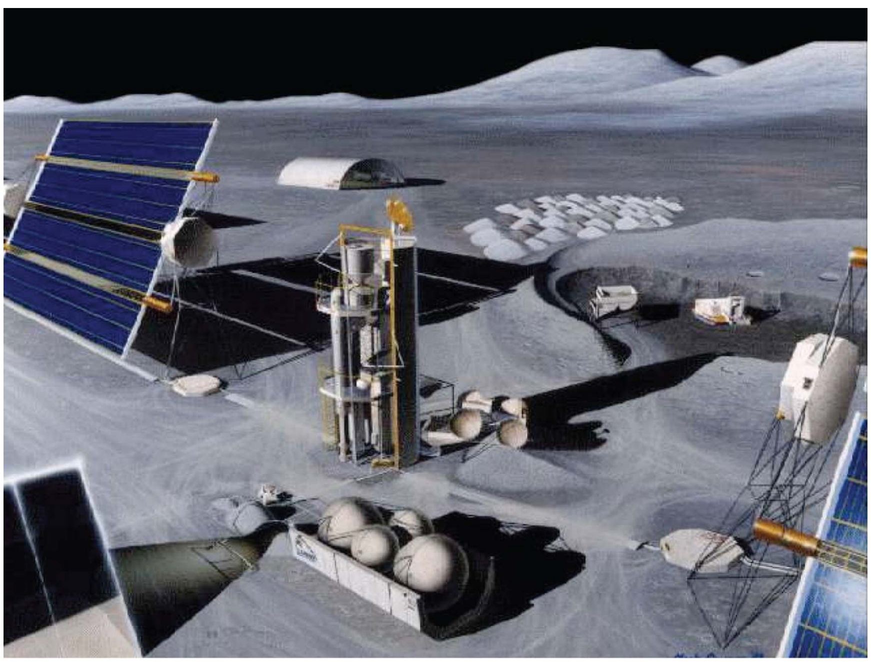

Figure 2.—Photovoltaic array powered oxygen production on the lunar surface (Ref. 2).

a photovoltaic array based system is well developed from extensive terrestrial and orbital use and the lunar environment does not pose a significant obstacle to its implementation. A photovoltaic power system will consist of a photovoltaic array, battery bank, charge controller and a peak power tracker. The array can either be fixed or tracking. The required tracking motion will influence the array design. This motion will be based on the latitude the array is operating at. For example at the lunar poles, the array would need to circle around with a small change in elevation angle, while at the equator the array would need to track 180° overhead (vertical to horizontal to vertical).

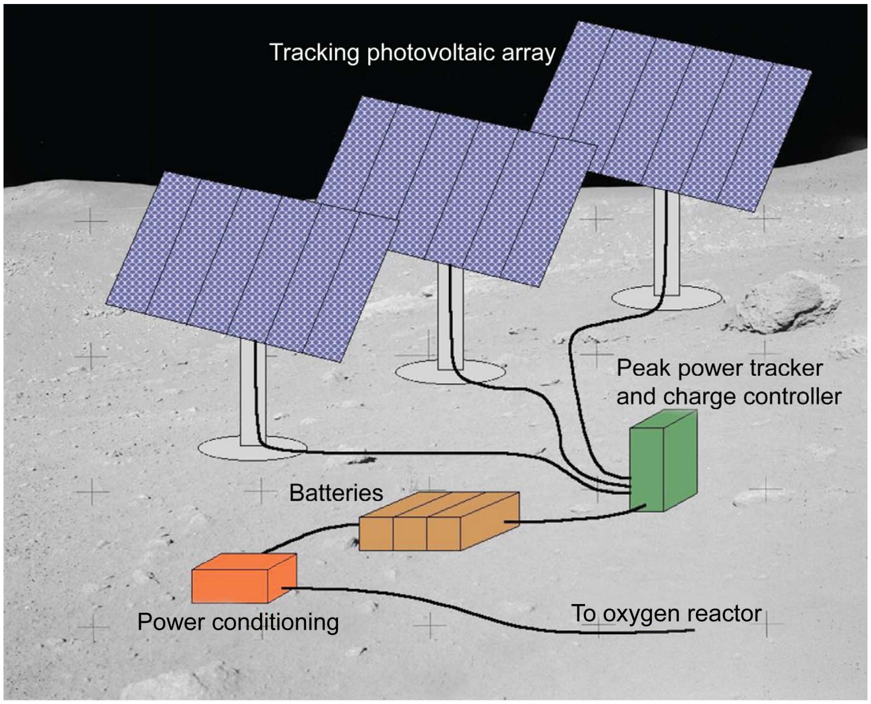

Figure 3.—Tracking photovoltaic array system layout.

Because the array is a current limited power source, a battery bank is required to regulate the power bus and insure sufficient power is available to meet spikes in power demand from the load. These spikes can be generated during device startup or during points of normal operation.

To provide the greatest amount of power for the installed array area, a tracking array system would be required. The tracking system would be able to continuously point the array toward the sun providing normal solar incidence on the array surface. A diagram of a tracking array system is shown in Figure 3. The tracking array system consists of the following components:

(1) Photovoltaic array panels
(2) Peak power tracker and battery charge controller
(3) Battery bank
(4) Power conditioning electronics

To enable normal incidence of the solar flux onto the array throughout the day, the photovoltaic array panels will need to have a 2-axis tracking capability. The batteries are utilized in this system as a means of providing a high current source for equipment startup and to handle any peaks or transients in the load power requirements. This is a more mass efficient approach then over-sizing the array to meet these requirements.

A similar photovoltaic array system was also sized based on a fixed tent shaped solar array. An illustration of a tent array is shown in Figure 4 and the tent based array system layout is shown in Figure 5.

A 60° tent array will provide a flat power profile throughout the day period. This type of array configuration provides about 42 percent of the output power as that of the tracking array on average throughout the day (Ref. 3). A comparison of the output of a tent array at various latitudes and a tracking array is shown in Figure 6.

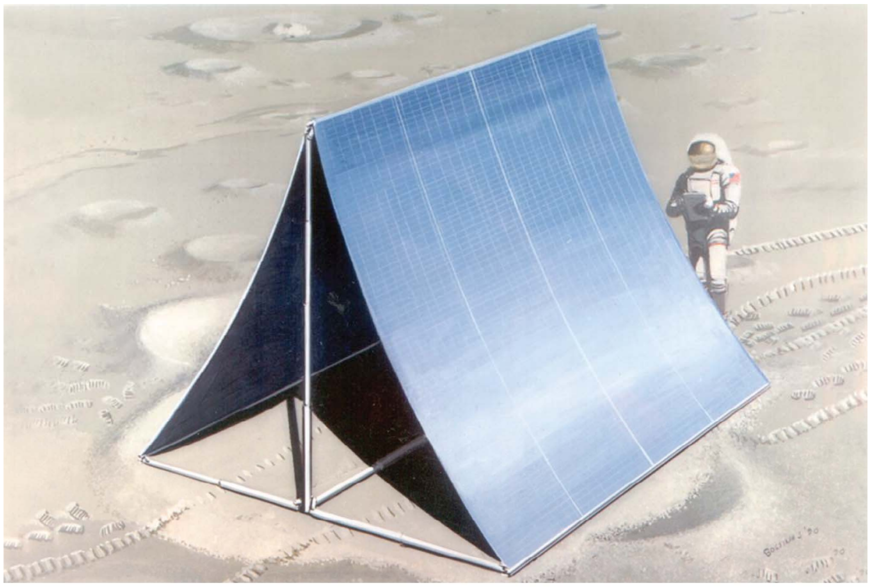

Figure 4.—Photovoltaic tent array concept (Ref. 3).

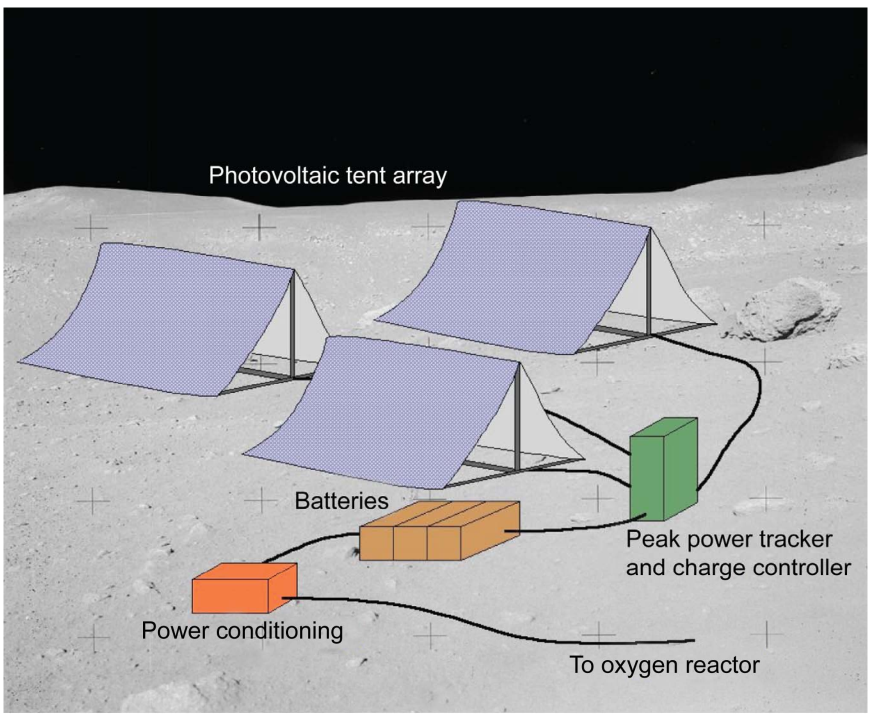

Figure 5.—Photovoltaic tent array system layout.

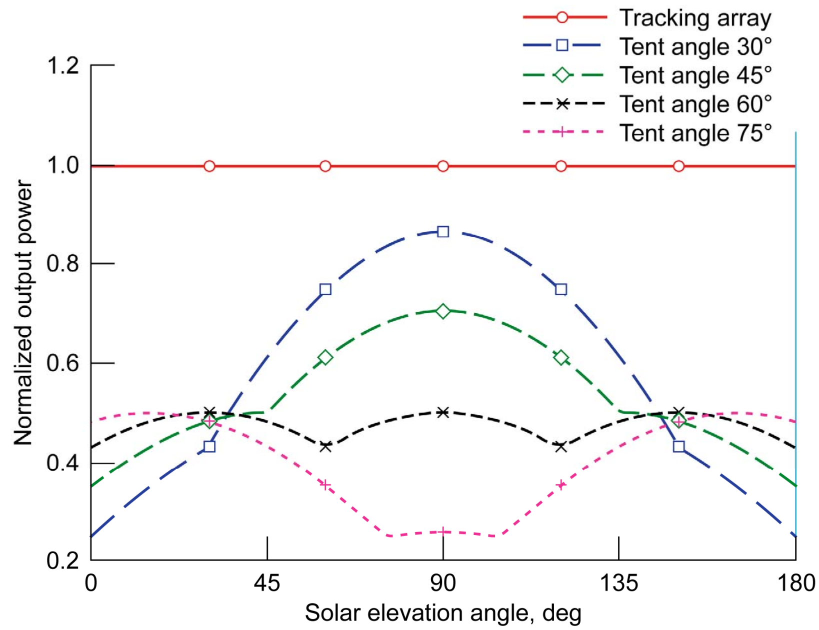

Figure 6.—Power output throughout the day for a tent array at various angles and a tracking array (Ref. 3).

To estimate the mass of the array, the power output and mass of a number of terrestrial panels were used. From these terrestrial panels an average specific mass of the terrestrial panels was determined; this value is given in Table 1 for rigid cell arrays and in Table 2 for the flexible arrays. The rated output power for the panels listed in these tables is for 1000 W/m^2 incident solar radiation. This average terrestrial panel specific power was then scaled to account for the higher available solar flux at the lunar surface and reductions in mass of the space arrays over those of the terrestrial arrays due to estimated improvements in the structure design and materials. A scaling factor corresponding to approximately a 2/3 reduction in the panel specific mass was used for the fixed nontracking lunar array. For the tracking array a reduction in specific mass of approximately 50 percent was used.

TABLE 1.—TERRESTRIAL RIGID PANEL ARRAY MASS AND POWER

Panel	Mass, kg	Area, m^2	Power output, W	W/m^2	W/kg	kg/m^2
M55	5.6	0.43	55	129	9.9	13.0
SX-170B	15.0	1.26	170	135	11.3	11.9
ES190-SL	18.2	1.50	190	127	10.4	12.2
GEPV-200	17.7	1.44	200	139	11.3	12.3
1KA-GSA	13.7	0.95	60	63	4.4	14.4
KC130GT	15.0	0.93	130	140	8.7	16.1
PV-MF170EB	15.5	1.26	170	135	11.0	12.3
PW1650-165	18.0	1.36	165	121	9.2	13.3
HIP-205BA3	14.0	1.18	205	174	14.6	11.9
S-170-SPU	15.5	1.26	170	135	11.0	12.3
ND-208U1	21.0	1.63	208	128	9.9	12.9
175-PC	17.3	1.32	175	132	10.1	13.1
SW165	15.0	1.30	165	127	11.0	11.5
STP170S	15.5	1.28	170	133	11.0	12.1
SW160	20.0	1.30	160	123	8.0	15.4
Average	15.8	1.23	160	129	10.1	13.0

For the flexible arrays, since the panel values listed in Table 2 have no structure associated with them, an additional 0.5 kg/m^2 was added for the flexible fixed array and 1.0 kg/m^2 was added for the flexible tracking array to account for support structure on the array.

TABLE 2.—FLEXIBLE PANEL ARRAY MASS AND POWER

Panel	Mass, kg	Area, m^2	Power output, W	W/m^2	W/kg	kg/m^2
PVL-136	7.7	2.16	136	62.92	17.66	3.56
R15-1200	0.88	0.567	18.48	32.61	21	1.55
AMSi-1 (array sample)	0.00215	0.00825	------	------	------	0.26
AMSi-2 (array sample)	0.0935	0.0853	------	------	------	1.09

Different types of photovoltaic cells were considered in the system layouts shown in Figures 3 and 5. To determine the total mass of the systems with different types of array panels each component was scaled, as a function of the amount of power the system was to produce. The specific power and area values used to scale each of the components are given in Table 3.

TABLE 3.—PHOTOVOLTAIC ARRAY SYSTEM'S SCALING MASS AND EFFICIENCY VALUES

Component	Specific mass tracking	Specific mass fixed tent	Efficiency
Single crystal silicon array	6.48 kg/m^2	4.86 kg/m^2	0.15
Gallium arsenide array	6.48 kg/m^2	4.86 kg/m^2	0.22
Triple junction array	6.48 kg/m^2	4.86 kg/m^2	0.29
Amorphous silicon array	2.62 kg/m^2	2.12 kg/m^2	0.01
Power conditioning	3.80 kg/kw	3.80 kg/kw	0.95
Charge controller/PPT	1.36 kg/kw	1.36 kg/kw	0.95

Concentrator System

The main difference between the concentrator and photovoltaic array, with regard to the oxygen production application, is that the concentrator can be utilized to directly produce heat. Since thermal energy is a significant portion of the total energy needed for the oxygen production system, the ability to generate this heat with minimal losses provides a large benefit to the concentrator system over a photovoltaic array. In order for a concentrator to operate effectively it must track the sun. Therefore, from the system perspective, there is no fixed version of the concentrator system, as there is with the photovoltaic array. The layout of a concentrator system and the main components are shown in Figure 6. The system consists of tracking concentrators that focus and concentrate light onto fiber optic lines. This light is then transferred to the oxygen reactor to provide heat as well as to the Stirling heat engines to provide electrical power.

Both rigid and flexible versions of the concentrator were evaluated. The rigid type consists of fixed mirrors held in a rigid structure and set on a tracking system to follow the motion of the sun. An example of a terrestrial rigid concentrator is shown in Figure 7.

The flexible concentrator is constructed from either an inflatable or other flexible membrane that is held in shape through wire or material tension or by other properties of the material. An example of a flexible concentrator is shown in Figure 8. A similar tracking system as that used with the rigid concentrator is needed with the flexible one in order to track the sun. Since no applicable concentrator designs were available to use for estimating the specific mass of both the flexible and rigid concentrators, the values of specific mass for the rigid and flexible tracking photovoltaic arrays were used to size the concentrators. This assumption was made since both systems will require similar tracking mechanisms and the materials for the PV arrays are similar in density to those the concentrator would be composed of. The specific mass values used in the analysis for the concentrator systems are given in Table 4.

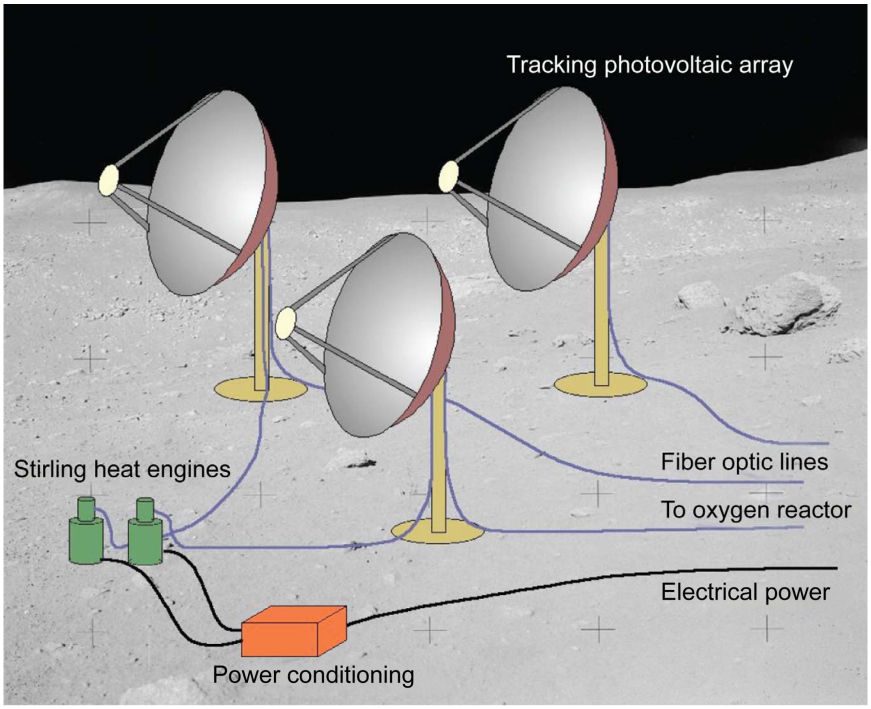

Figure 7.—Concentrator system layout.

Figure 8.—Terrestrial fixed panel, rigid solar concentrator.

TABLE 4.—CONCENTRATOR SYSTEM'S SCALING MASS AND EFFICIENCY VALUES

Component	Specific mass tracking	Efficiency
Rigid concentrator	6.48 kg/m^2	0.81
Flexible concentrator	2.62 kg/m^2	0.72
Power conditioning	3.80 kg/kw	0.95
Stirling engine	20 W/kg	0.35

Mass Results for Complete Concentrator and PV Array Systems

Each type of photovoltaic array and concentrator system was sized to determine its mass for a specified power level. The power levels were determined based on the power required to produce a specific amount of oxygen. These power levels were for the production of oxygen through the hydrogen reduction of illminite process and were based on the analysis described in Reference 1. It should be noted that, since the scaling numbers used were estimates and not based on any actual array or concentrator, the mass scaling used between similar functioning systems was identical. For example the mass scaling between the rigid cell tracking photovoltaic arrays an the rigid concentrator was the same at 6.48 kg/m^2, as well as between the flexible tracking photovoltaic array and the flexible concentrator at 2.62 kg/m^2. This was done as a means of minimizing any bias toward a particular system since no actual array or concentrator design were available.

The required mass of each system as a function of the oxygen production rates is shown in Figures 9 through 11. Figures 9 and 10 show the comparison between the masses of the tracking and fixed tent photovoltaic array systems to that of the solar concentrator systems, respectively. The masses were calculated over a range of oxygen production rates, from 0.1 to 1 kg/hr. Figure 11 provides a comparison of the mass of all the systems examined over a range of oxygen production rates.

The results, in Figures 9 through 11, show that the concentrator system provides the lowest mass option for providing both electrical and thermal power to the oxygen production system. The tracking PV array system masses were in general lower then the fixed tent array masses with the triple junction photovoltaic array based system being the lightest of the array system.

The tracking triple junction system was also very close in mass to the rigid concentrator system. This indicates that high-efficiency solar cell can provide a mass benefit over other types of arrays and potentially be competitive to concentrators for this type of power system application. However, the high cost associated with very high efficiently solar cells would be a limiting factor when compared to a projected less costly concentrator system that is comparable mass wise.

Figure 9.—Inflatable concentrator under development by SRS Technologies.

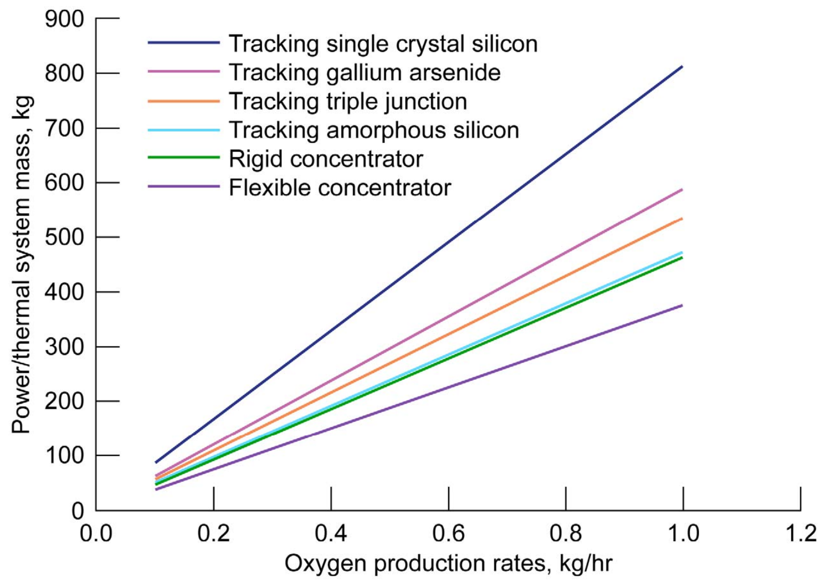

Figure 10.—Tracking array and concentrator mass versus oxygen production rates.

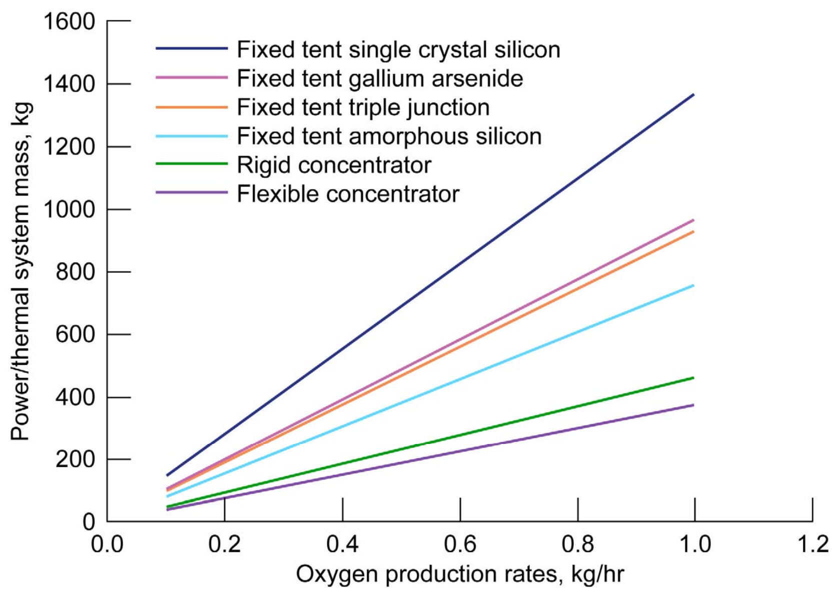

Figure 11.—Fixed tent array and concentrator masses versus oxygen production rate.

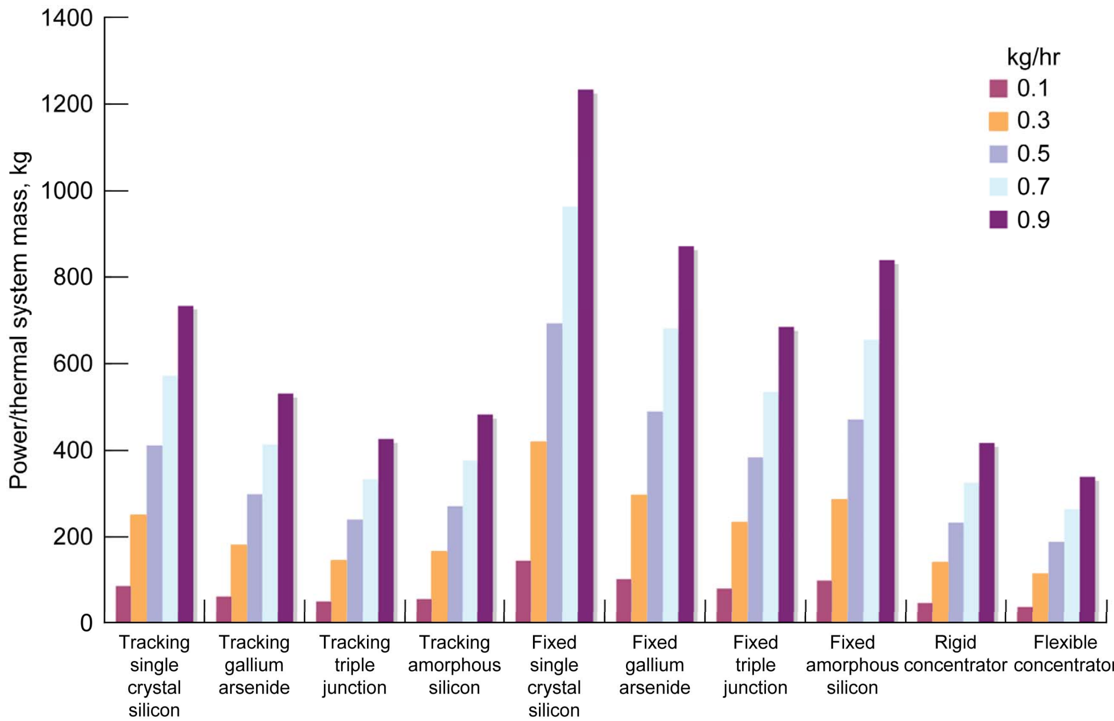

Figure 12.—Power system masses at various oxygen production rates.

A the mass breakdown for each system at an oxygen production rate of 0.5 kg/hr is given in Appendix A. Figures A1 through A8 show the mass breakdown for the various photovoltaic systems and A9 and A10 show the mass breakdown for the rigid and flexible concentrator systems. The main contrast between the array and concentrator systems is that for the arrays the photovoltaics are the main mass component where as for the concentrator it is the Stirling engine electrical power conversion component.

In addition to the total mass of the system given in the previous figures and in Appendix A the system specific power can also be calculated as a means of comparing the various types of power systems being considered. The specific power (in W/kg) is the total required power, both thermal and electrical, needed to produce a given amount of oxygen divided by the total mass of the system. Since the required power scales linearly with the oxygen production rate, as seen in Figure 1, the specific mass of a given system is a constant regardless of the required production rate. The specific mass for the various systems was calculated and is given in Figure 12.

Form Figure 12 it can be seen that both the concentrator systems provide the highest specific mass with the flexible concentrator being the highest. The tracking triple junction solar array system has the highest specific mass of the array types considered and is only slightly less then the rigid concentrator system.

An estimate of the present level of development (technical readiness level, TRL) for the power systems that were considered in the context of a Lunar surface ISRU application are shown Table 5. A definition of each TRL level is given in Appendix B. The estimation of the present TRL level for each of the power system types is given based on the complete system development as it would be applied to the ISRU application. However it should be noted that the individual components of the systems will range in development level. For example many of the types of solar photovoltaic arrays have been used in space and would warrant a TRL of 7 or 8 for the lunar application. Whereas the tracking or deployment system needed for their implementation would be at a TRL of 4. Because of this variation in the relative development of different aspects of the complete system a TRL range was used for assessing each system type.

TABLE 5.—LUNAR ISRU POWER SYSTEM DEVELOPMENT LEVEL

System	TRL
Tracking single crystal silicon	5 to 8
Tracking gallium arsnide	5 to 8
Tracking triple junction	5 to 8
Tracking amorphous silicon	5 to 6
Fixed single crystal silicon	6 to 8
Fixed gallium arsnide	6 to 8
Fixed triple junction	6 to 8
Fixed amorphous silicon	6
Rigid concentrator	4 to 6
Flexible concentrator	3 to 5
Batteries	8
Power electronics	6 to 8
Stirling engine	3 to 6
Electrolyzer	3 to 6
Tracking single crystal silicon	5 to 8
Tracking gallium arsnide	5 to 8

Mass Results for Hybrid PV Array and Concentrator System

Since the power requirements for the oxygen production process utilize both thermal and electrical power levels of the same magnitude (Fig. 1) it is worth considering a hybrid type power generation scheme in which separate power sources were used to produce the thermal and electrical power. An example of this hybrid type system would be to utilize a concentrator for providing the thermal power and the PV array for providing electrical power. Also the electrical power could be supplied from an already established outside source and only thermal power would be needed.

This hybrid system can be evaluated and compared to a single source system by looking at the component masses for both of the main power requirements separately and summing them to provide a total mass requirement. To be consistent with the previous analysis and to provide a means of comparing a hybrid type system with the systems previously analyzed the same rate of oxygen production range (0.1 to 0.9 kg/hr) and associated power requirements was utilized.

The system mass of a hybrid power system utilizing a rigid concentrator with the various types of PV arrays is shown in Figure 13. The overall mass for each system is less then the comparable PV system shown in Figure 11, although the mass trend is similar between the different types of arrays. Similar results were achieved by combining the different PV array systems with a flexible concentrator. These results for the hybrid PV array/flexible concentrator system are shown in Figure 14.

As with the single source power systems, the hybrid systems can be compared on a specific mass basis. The specific mass of both the hybrid power systems and single source systems is shown in Figure 15. From these results the tracking triple junction hybrid system provides the highest specific mass for both types of concentrators. Overall the flexible concentrator hybrid systems had the highest specific mass for each type of array technology.

The results shown in this section indicate that a mass savings can be achieved by utilizing a hybrid type of power system where the electrical power is generated by a PV array and a solar concentrator generates the thermal power. A hybrid power system provides a unique approach to the generation of power for oxygen production. In a way it optimizes both the electrical and thermal power sources. It eliminates the need to produce heat from the power supplied by the photovoltaic array and generates this heat directly utilizing the solar concentrator. This significantly reduces the inefficiencies associated with producing electricity and then turning that electricity into heat, as is required by a single source system. It also eliminates the heaviest component of the single source concentrator system, the Stirling heat engine, and replaces it with the lighter solar array for generating electrical power. Utilizing a solar array to generate electrical power to operate the system equipment reduces the mass over that of the Stirling converter.

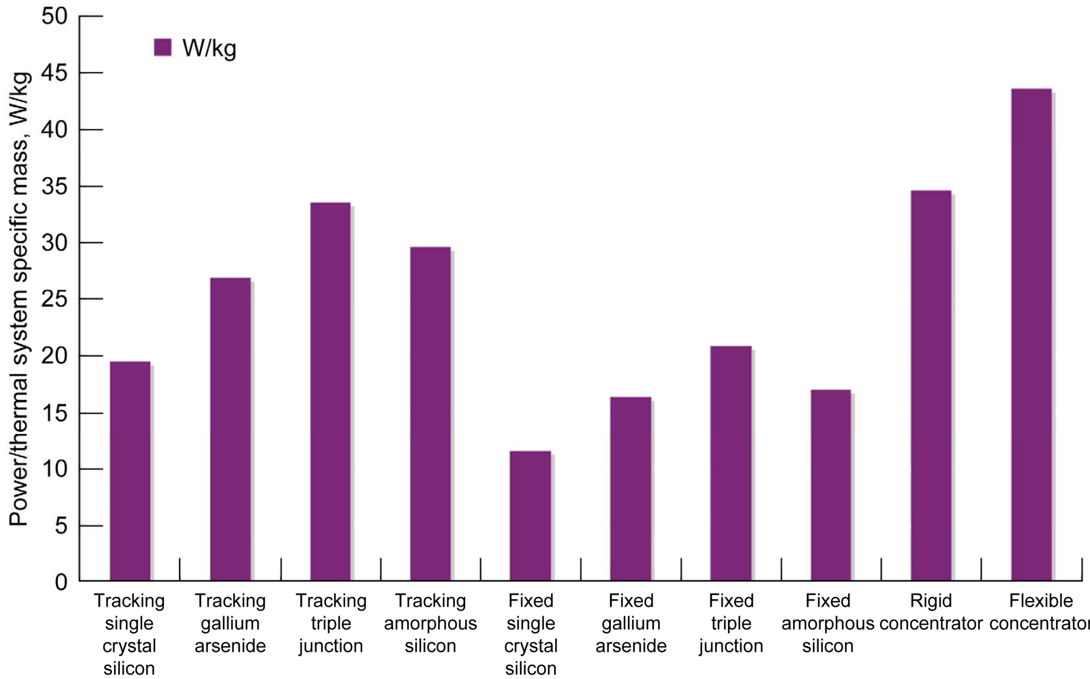

Figure 13.—System specific mass for the various types of power systems.

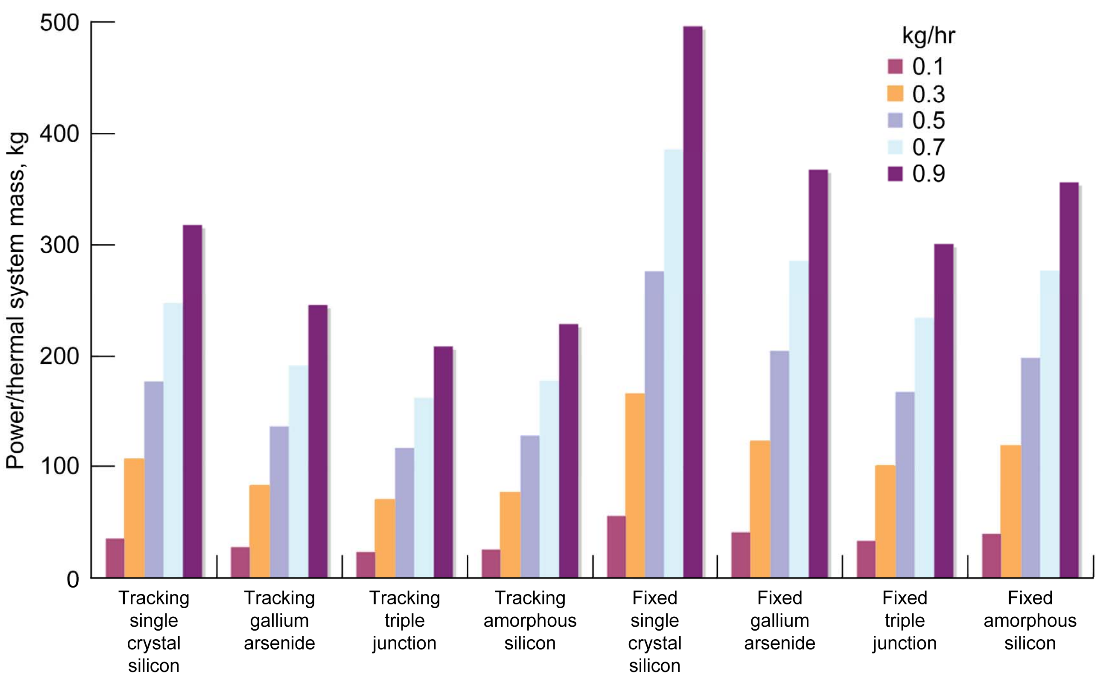

Figure 14.—Hybrid power system mass with a rigid concentrator.

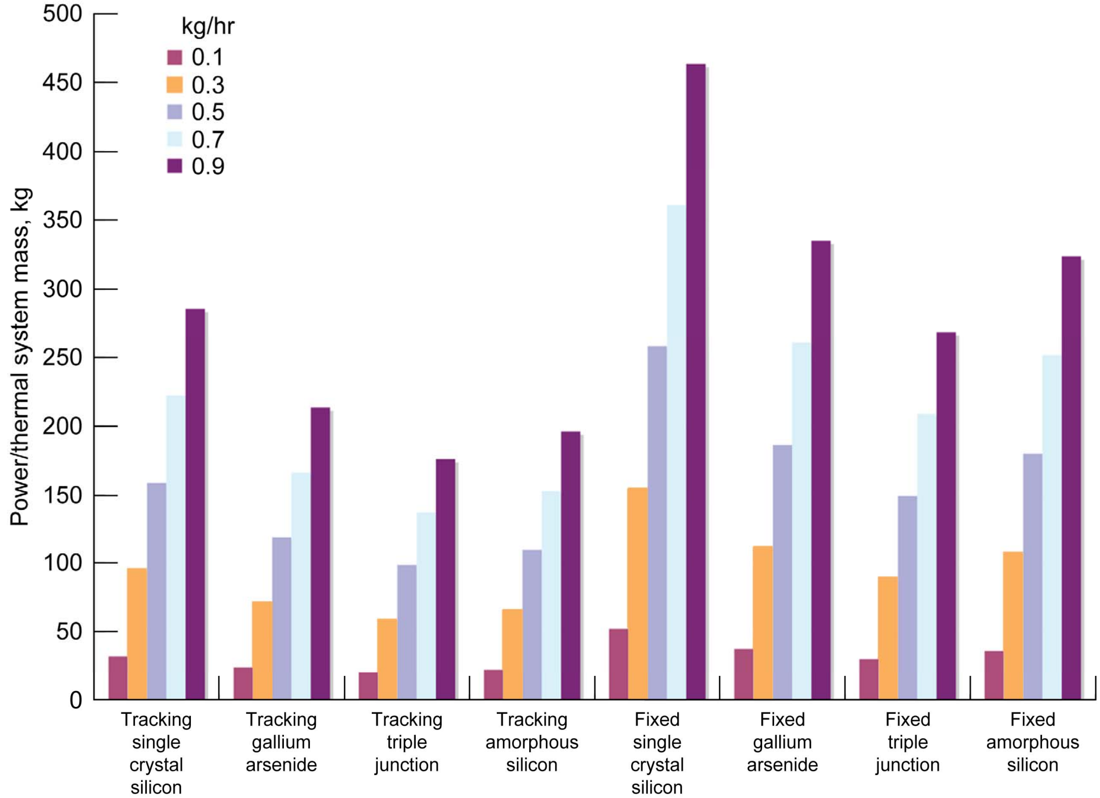

Figure 15.—Hybrid power system mass with a flexible concentrator.

A hybrid system can also enables the use of a previously deployed power system. For example if a PV array was previously deployed on the surface for a separate application it could be reutilized to provide electrical power to the system, with a concentrator providing the thermal power.

However, there are other aspects to this type of system that will need to be considered. The main concerns with a hybrid system are:

(1) Since two separated power sources will need to be deployed on the lunar surface the overall complexity of this system will be greater then a single source system.

(2) The overall volume of the hybrid system will likely be larger then a single source system. The volume issue can be addressed when a detailed system design is performed.

The final comparison between the systems is in the production of the required thermal energy only. In the case where an electrical power can be provided by a separate power source to operate the electrical equipment, only the thermal power requirement must be met. This type of system will favor a concentrator since the direct concentration of sunlight to produce heat is more efficient then converting that sunlight into electricity and then to heat, as is required by the photovoltaic systems. The specific mass results for this scenario, where only thermal energy is required from the system, is shown in Figure 16.

As expected, from Figure 17 it can be seen that the concentrator systems provide a significant increase in power system specific power over the photovoltaic systems for generating heat. The flexible concentrator system produces the highest specific power due mainly to the reduced weight of the concentrator itself over that of a rigid concentrator system. It should be noted that, depending on the temperature requirements for the oxygen reactor, the use of a flexible concentrator may not be possible due to limitation on its concentration ratio. For this study this effect was not considered. However, the specific power values for the flexible concentrator system do reflect the type of increase in specific power that can be achieved by reducing the concentrator mass.

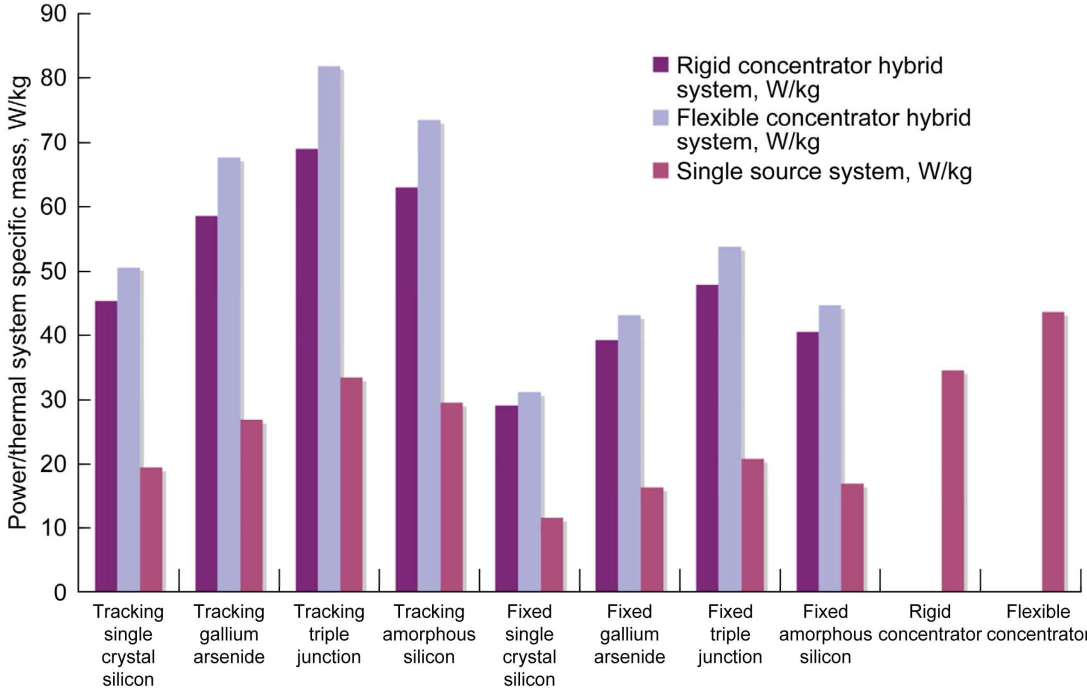

Figure 16.—Single source and hybrid power system specific masses.

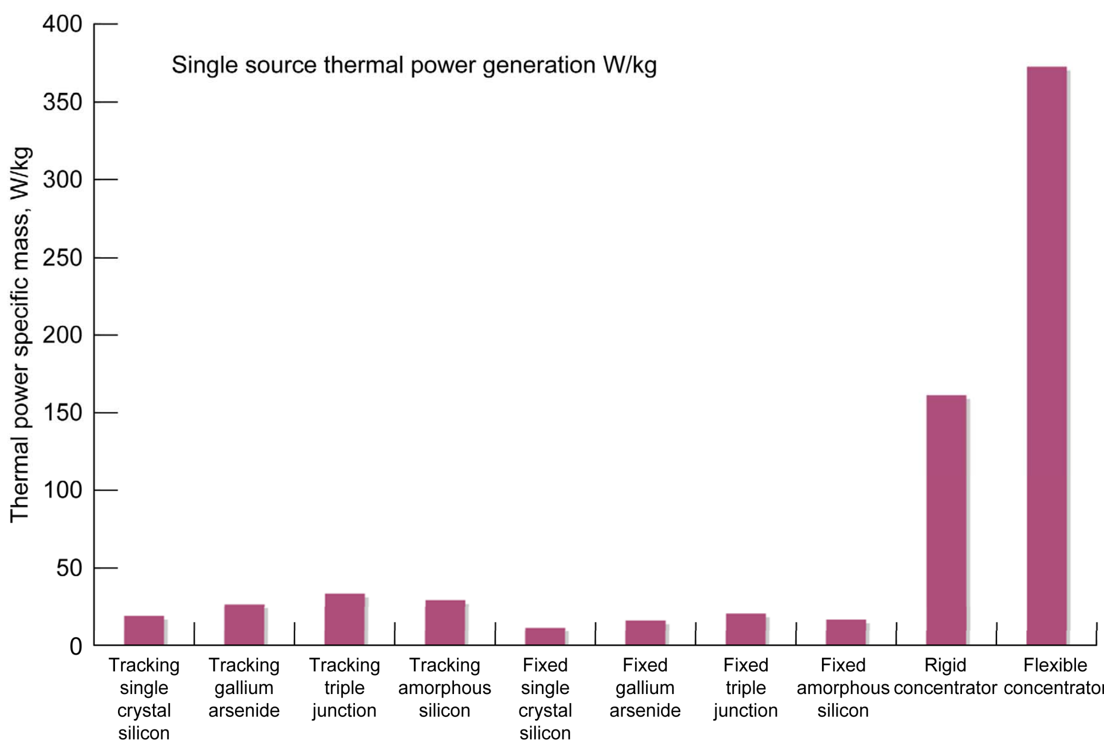

Figure 17.—Power system specific mass for thermal power generation.

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Appendix A—System Mass Breakdown

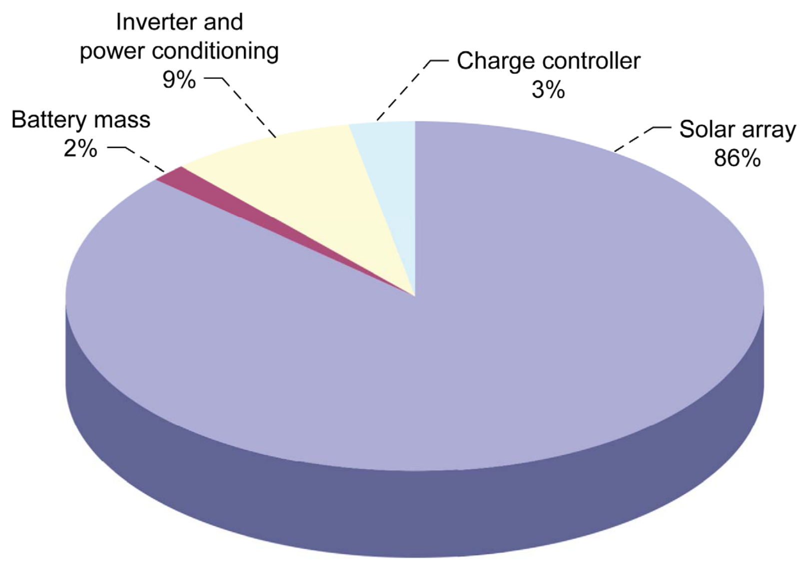

Figure A1.—Mass breakdown for single crystal silicon tracking array system (total mass 411 kg) at 0.5 kg/hr oxygen production rate.

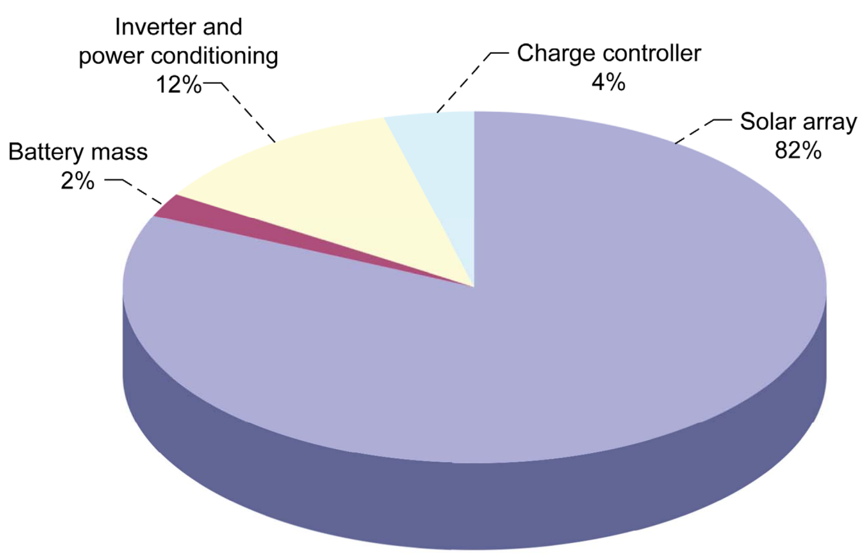

Figure A2.—Mass breakdown for gallium arsenide tracking array system (total mass 298 kg) at 0.5 kg/hr oxygen production rate.

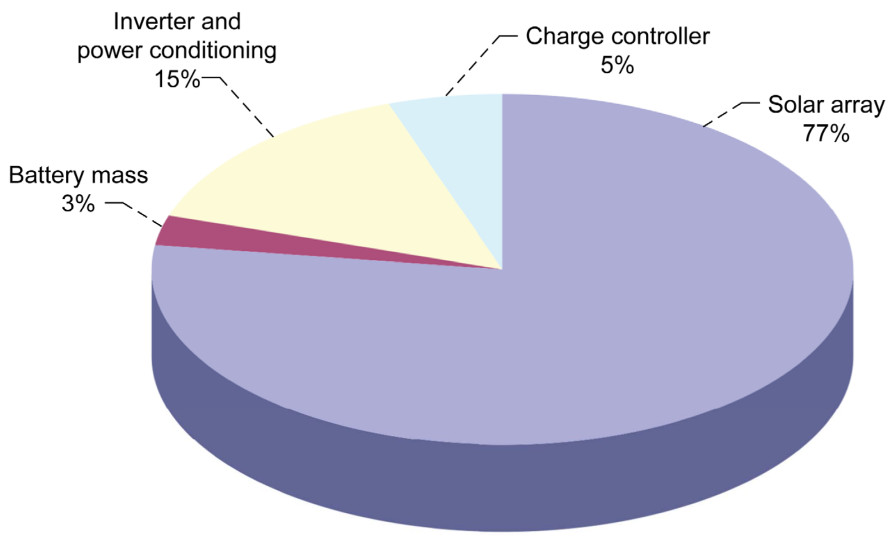

Figure A3.—Mass breakdown for triple junction tracking array system (total mass 239 kg) at 0.5 kg/hr oxygen production rate.

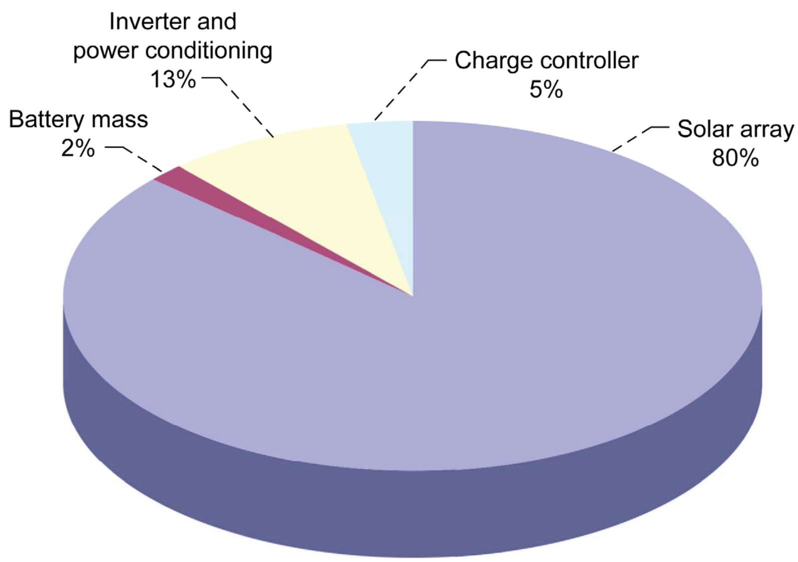

Figure A4.—Mass breakdown for amorphous silicon tracking array system (total mass 271 kg) at 0.5 kg/hr oxygen production rate.

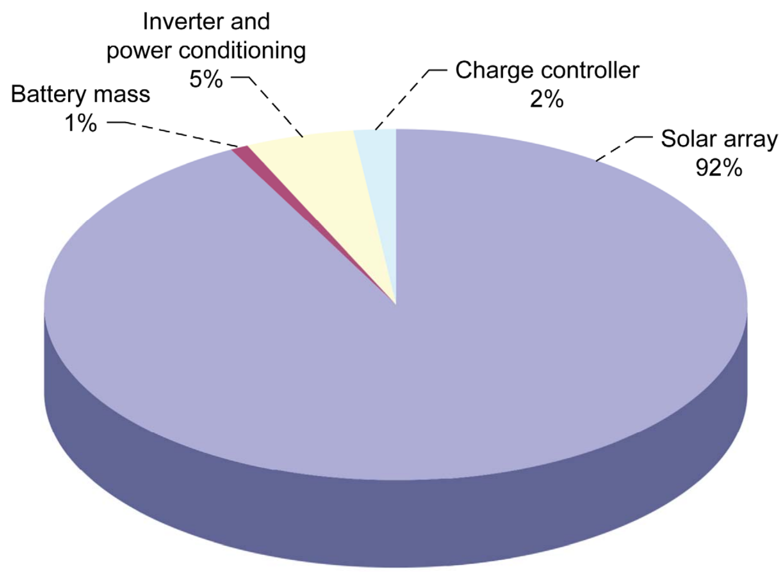

Figure A5.—Mass breakdown for single crystal silicon tent array system (total mass 692 kg) at 0.5 kg/hr oxygen production rate.

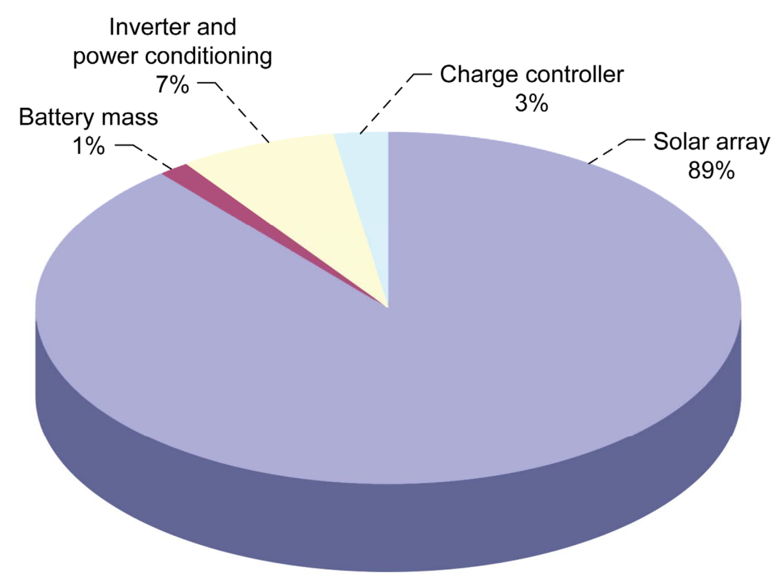

Figure A6.—Mass breakdown for gallium arsenide tent array system (total mass 489 kg) at 0.5 kg/hr oxygen production rate.

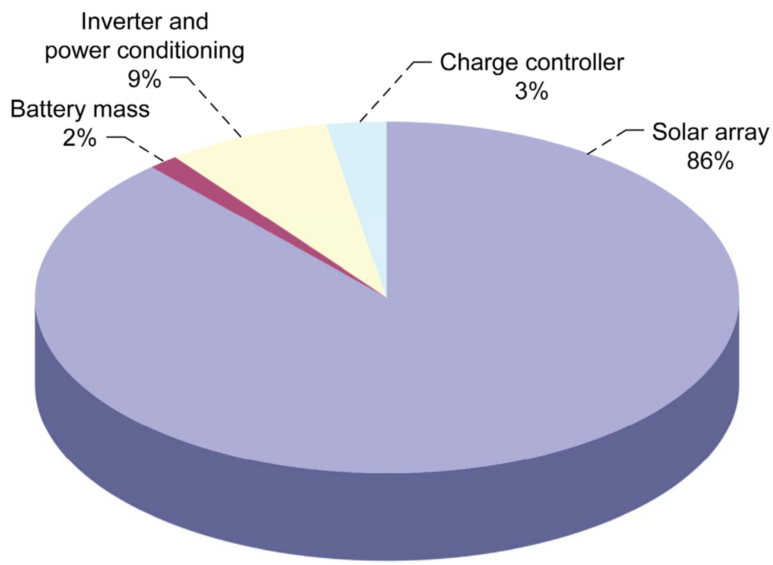

Figure A7.—Mass breakdown for triple junction tent array system (total mass 384 kg) at 0.5 kg/hr oxygen production rate.

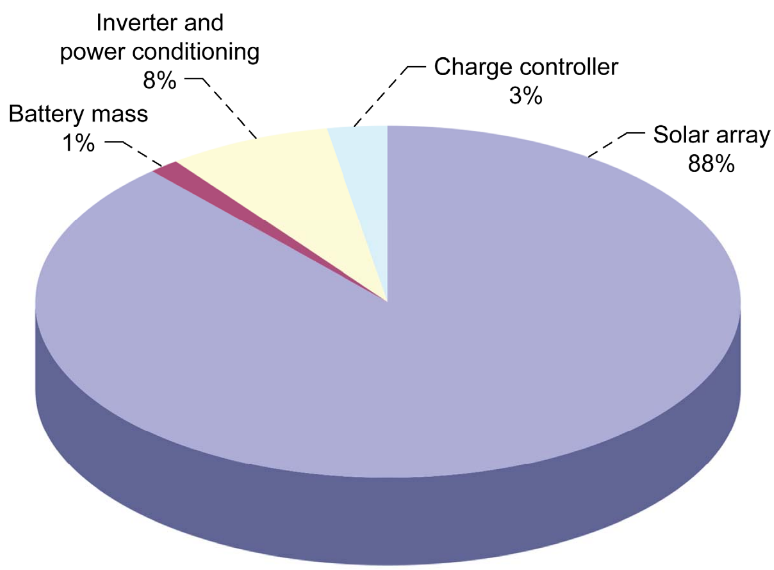

Figure A8.—Mass breakdown for amorphous silicon tent array system (total mass 471 kg) at 0.5 kg/hr oxygen production rate.

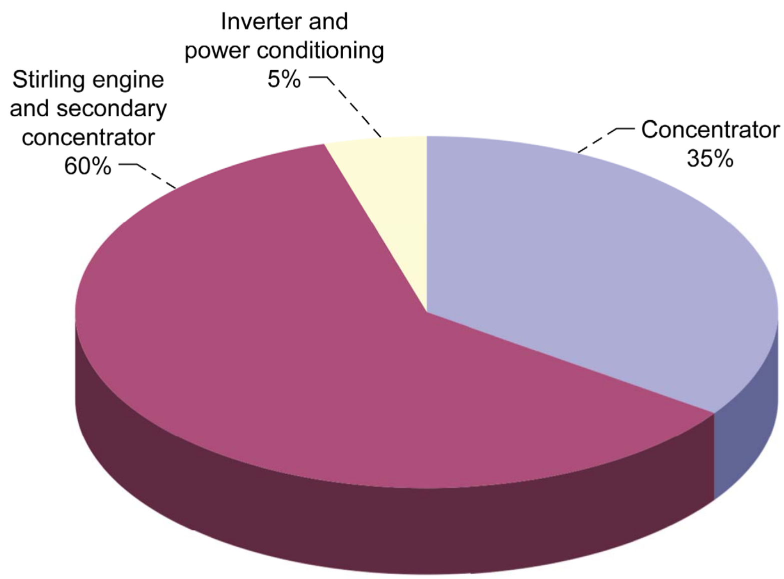

Figure A9.—Mass breakdown for rigid concentrator system (total mass 232 kg) at 0.5 kg/hr oxygen production rate.

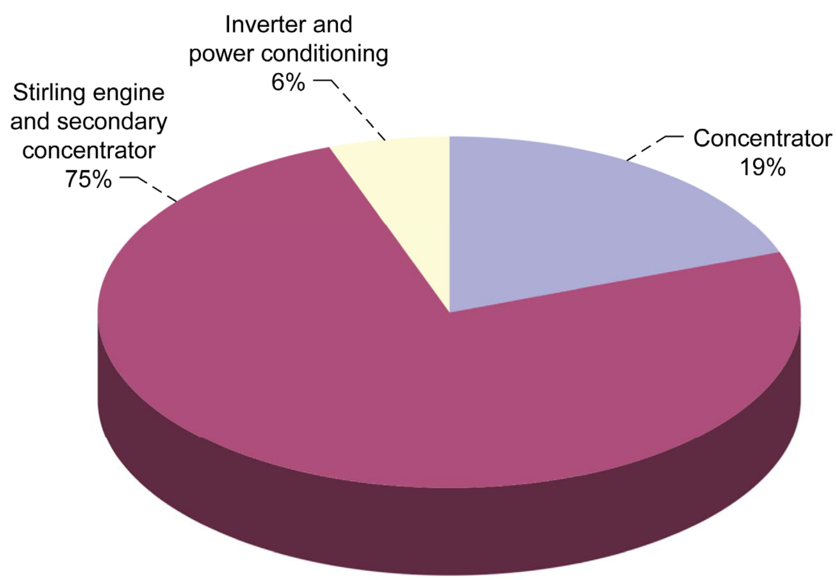

Figure A10.—Mass breakdown for flexible concentrator system (total mass 189 kg) at 0.5 kg/hr oxygen production rate.

Appendix B—TRL Level Definition

Level 1	Basic Principles Observed and Reported
Level 2	Technology Concept and/or Application Formulated
Level 3	Analytical and Experimental Critical Function and/or Characteristic Proof-of Concept
Level 4	Component and/or Breadboard Validation in Laboratory Environment
Level 5	Component and/or Breadboard Validation in Relevant Environment
Level 6	System or Subsystem Model or Prototype Demonstration in a Relevant Environment (Ground or Space)
Level 7	System Prototype Demonstration in a Space Environment
Level 8	Actual System Completed and Flight Qualified Through Test and Demonstration (Ground or Space)
Level 9	Actual System Flight Proven Through Successful Mission Operations

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The production of oxygen from the lunar regolith requires both thermal and electrical power in roughly similar proportions. This unique power requirement is unlike most applications on the lunar surface. To efficiently meet these requirements, both solar PV array and solar concentrator systems were evaluated. The mass of various types of photovoltaic and concentrator based systems were calculated to determine the type of power system that provided the highest specific power. These were compared over a range of oxygen production rates. Also a hybrid type power system was also considered. This system utilized a photovoltaic array to produce the electrical power and a concentrator to provide the thermal power. For a single source system the three systems with the highest specific power were a flexible concentrator/Stirling engine system, a rigid concentrator/Stirling engine system and a tracking triple junction solar array system. These systems had specific power values of 43, 34, and 33 W/kg, respectively. The hybrid power system provided much higher specific power values then the single source systems. The best hybrid combinations were the triple junction solar array with the flexible concentrator and the rigid concentrator. These systems had a specific power of 81 and 68 W/kg, respectively.

15. SUBJECT TERMS
Solar collector; Concentrators; Thermal energy; Solar arrays

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